Babcock · Vaults · 1884

VAULTS.

By Professor Charles Babcock.

BOSTON:
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VAULTS.

It is proposed in this treatise to explain and illustrate the various forms of vaulting. The importance of the subject in the study of architecture need not be dilated upon here; nor, for our purpose, is the precise historical order of development of any special moment. In making notes on vaulting, by way of preparation for the instruction of students, the author was surprised at the paucity of illustrations in any one work — saving Viollet-le-Duc's Dictionnaire Raisonné de l'Architecture — and the absence of any attempt to classify the various forms. He therefore set about collecting, drawing and arranging a continuous and orderly series of examples. The result of his labors is here submitted for the benefit of those who desire to obtain a clear and comprehensive view of the subject. The reader will probably find, in his travels and investigations, many examples that apparently do not conform to any of the regular and typical shapes that are here presented; but if he studies carefully such as are given, he will have no difficulty in analyzing the odd, fanciful, distorted and irregular forms that he may meet with.

The analytical order is adopted as the only feasible one. The historical would require separate treatment for the examples from each country. The simplest forms are, of course, the earliest; but in some cases they are the latest also, and in others they prevail, almost to the exclusion of the more complex, throughout the entire period of a style. The object here is not to give the history of vaulting, but to set forth its principles of construction, and to show the forms which it assumes. As a rule, only existing specimens will be presented; and one example at least will be named under each division. Precise dates are often unknown, uncertain, or disputed, and the reader must take upon himself the trouble of ascertaining them.

Vaults may be divided as follows: As to mode of construction into SOLID and RIBBED. As to form into SIMPLE and COMPOUND.

SOLID VAULTING — SIMPLE.

I. The simplest form of vault is that which is known as the barrel, tunnel, cradle or wagon vault. It is merely an arch extended in the direction of its axis so as to cover a space or compartment of a building. The typical form, and the most common, though perhaps not the oldest, is the cylindrical (Fig. 1), the cross-section being semi-circular, and the intrados, generally termed the "vaulting surface," a portion of the surface of a hollow cylinder. A barrel-vault may, however, have its cross-section semi-elliptical, segmental, pointed, three-centred, four-centred, etc. It may be constructed of brick, stone, or concrete. When it is of stone or brick, the leading or coursing-joints are usually parallel to the axis, and the cross-joints in planes perpendicular to the axis. The coursing-joints we shall designate simply as "the joints."

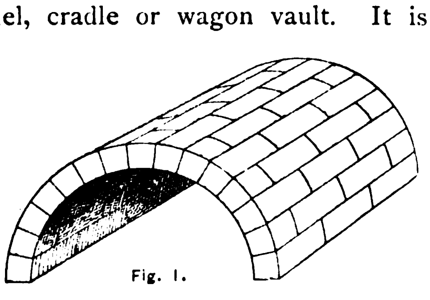


Fig. 1.

Barrel-vaults are very common and very ancient. Examples, both cylindrical and pointed, are found at Nimroud and in the pyramids at Meroë, which must be dated as far back as 800 B. C. There is a very perfect one of stone, in four rings, covering the chamber of a tomb at Ghizeh, dating about 600 B. C. (Fig. 2). The angular structure beneath it is a vault with plane surfaces. The Cloaca Maxima is a well-known Roman example, of stone, in three rings, generally stated, but probably incorrectly, to have been built as early as 400 B. C. In all the above cases the vault is merely a mechanical or engineering work used in places where it could not be seen, and having no properly architectural features. It was a device for covering spaces with materials of small size, instead of with large slabs of stone. Its inventors seem to have been ashamed of it. The Romans adopted it as a visible structure, worthy of ornamentation. They turned barrel-vau'ts, for instance, over the cells of their temples, to form ceilings. It may here be noted that in architectural structures vaults are generally ceilings only, not roofs. Those in crypts carry the floor above them; and sometimes, as in Milan Cathedral, and notably, in the Romanesque buildings of southern France, the nave and aisle vaults carry a solid roof of masonry. (Fig. 3). It seems probable that the vaults of the earlier Byzantine churches served as both roofs and ceilings. Whether the great vaults of the Roman baths had roofs over them is a disputed question. It is quite certain, however, that in most cases vaults are but ceilings. They are to be seen, therefore, and their architectural effect is to be studied, from the interior; although the construction is often best exhibited in a drawing which gives an exterior view.

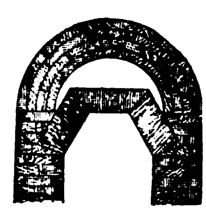


Fig. 2.

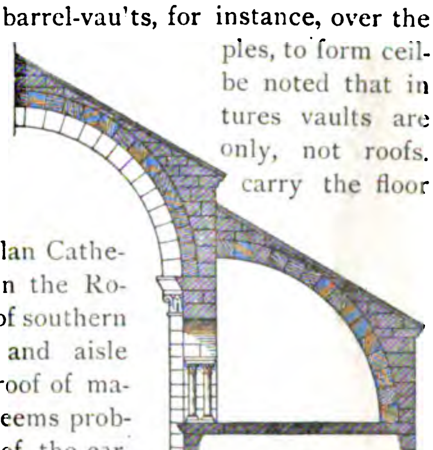


Fig. 3.

A barrel-vault usually covers a rectangular space, but sometimes a triangular one, as in the church built at Aachen by Charlemagne, or a trapezoidal, as at Nocera, in Italy. Its axis is commonly horizontal, but may be inclined, as it frequently is over a stairway.

Fig. 3 furnishes an example of the use of half barrel-vaults over aisles. These serve not only as roof, and ceilings, but also as continuous flying buttresses, receiving and resisting the outward thrust of the nave vaults. They are common in Auvergne, Languedoc, Lyonnais and Provence, being constructed about the year 1100. A very interesting illustration of a Roman method of building barrel-vaults of brick is given in Viollet-le-Duc's Dictionnaire Raisonné de l'Architecture, § 2.

II. A skew arch is a barrel-vault whose ends are in parallel planes oblique to the axis, and whose joints are spirals.

III. An annular vault has a curved axis, usually circular or elliptical. Its intrados is a portion of the surface of a cylindrical ring. Santa Costanza, Rome, built in the fourth century, is an example, a drawing of which is given in Gally Knight's Ecclesiastical Architecture of Italy.

IV. A spiral vault may be described as an annular vault having a spiral axis. It is used for supporting the steps of a winding stair. Examples occur at Kirby Muxloe Castle, England, (see Building News, Aug. 6th, 1875); at Colchester Castle, (Britton's Architectural Antiquities, Vol. I.); and Brixworth Church, (Britton's History of Architecture, Plate 2.)

V. Expanding vaults are larger at one end than at the other, and consequently have inclined ridges. Their surfaces are parts either of cones or conoids.

a. Conical vaults are quite common in Romanesque buildings, forming pendentives for reducing a square to an octagon. (Fig. 4.) The joints are radiating; the cross-joints are in planes parallel to the base of the cone. Such vaults are apparently not used, in their single form, for any other purpose; but they may form parts of compound vaults. There is an example, too, of a simple pointed vault, whose surfaces appear to be portions of two intersecting cones, over the choir galleries of Notre Dame de Mantes. (Fig. 5.) Its ridge is very nearly level.

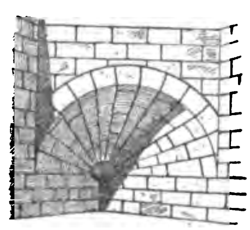


Fig. 4.

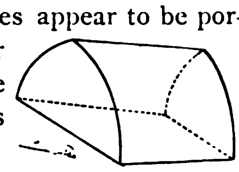


Fig. 5.

b. Fig. 6 represents an expanding vault in the form of a straight-sided conoid, whose smaller base is circular and larger base elliptical. It covers a rectangular space; *r r* is the ridge line. Used simply, as above, it is quite rare; but as part of a compound vault, as we shall see further on, it is very common. The joints are usually straight and radiating. If, however, the vault be pointed, as is often the case, being composed of parts of the surfaces of two such conoids, the joints may run spirally, appearing also, when viewed on a horizontal projection, to radiate from points beyond the larger ends of the conoids.

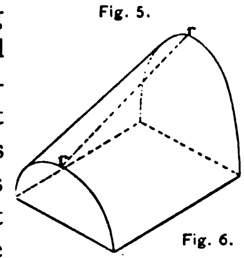


Fig. 6.

c. In the form shown in Fig. 7, the bases of the conoids are as in Fig. 6, and, as in that case, the elements of the surface at the springing are parallel to the axis, but the ridge is curved. Though the term may not be quite correct, we will call this a "convex-conoidal" vault. It rarely occurs single, but in compound vaults it is one of the most common forms, especially in Romanesque work.

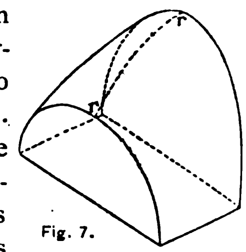


Fig. 7.

It may be composed of parts of two surfaces, and so be pointed.

SOLID VAULTING — COMPOUND.

COMPOUND vaults are formed by the intersection of two or more simple vaults, which may be barrel-vaults or expanding-vaults.

They are commonly known as "groined" vaults, the angle made by two surfaces being the groin angle. There are numerous varieties, which we will endeavor to classify.

A. QUADRIPARTITE. These are formed by the intersection of two barrel-vaults or four expanding vaults.

I. *For covering a square compartment.*

a. The common groined-vault, often called the Roman (Fig. 8), is formed by the intersection, at right angles, of two equal barrel-vaults, of any cross-section, but usually semi-circular. The groin-angle is 90 degrees at the springing, gradually becoming more and more obtuse towards the crown or centre. The groin-line is straight on the horizontal projection or plan. Its curve, projected on the plane in which it lies, depends upon that of the cross-section of the composing vaults. If the latter is circular or elliptical, the groin-line is elliptical. The ridges are level. The joints are parallel to the axes. Figure 9 is a quarter plan. The compartments are here shown as separated by cross bands, which are merely portions, thickened by a few inches, of the main vault, the one that runs lengthwise of the building. They may, however, be independent arches, but do not support the vaults. Professor Willis states that in the Piscina Mirabile near Baiæ, the "sub-arches are genuine ribs, strengthening and sustaining the vault, which is of tufa, while they are strongly built of brick or stone." In the drawing which he gives, however, the sub-arches or bands, project so little below the surface of the vault that it seems improbable

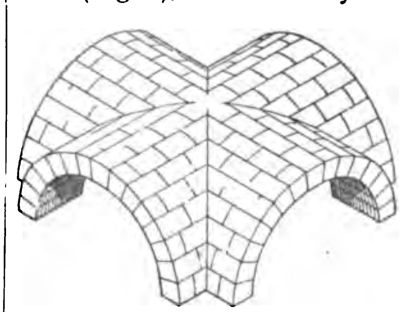


Fig. 8.

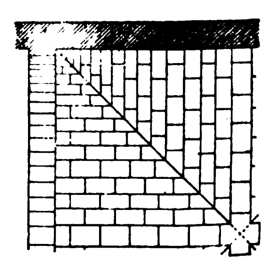
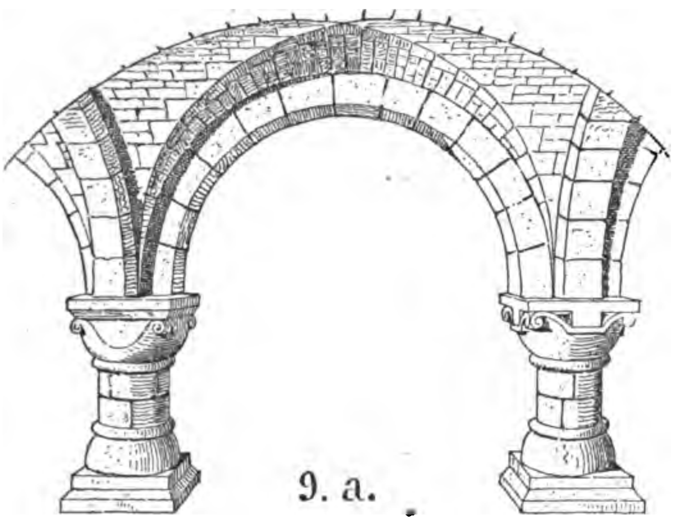


Fig. 9.

that the vault runs over their backs. It is possible that the construction is such as is shown in the section at a, Fig. 3, in which the cross-arch is a real rib, though showing only as a band. In Romanesque work the



9. a.

band is deepened and becomes a distinct arch, unde the vault, as in the crypt of Lastingham church, England. (Fig. 9 a).

b. Domical vaults. In these the centre is raised above the level of the apex against the cross-arch and wall, so that the ridges rise toward the centre. The

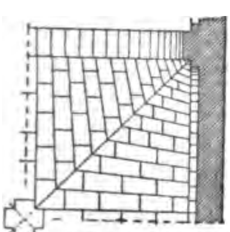


Fig. 10.

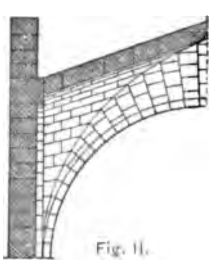


Fig. 11.

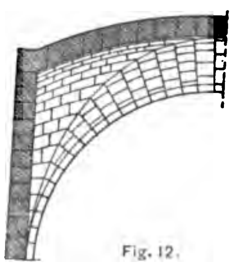


Fig. 12.

compartments, if there are more than one, must be separated by cross-arches or bands. In Santa Sophia, Constantinople, the cross-arch is a strip of barrel-vaulting showing no vertical faces but only the soffit. Domical vaults are formed, over square spaces, by the intersection of four equal expanding vaults, which may

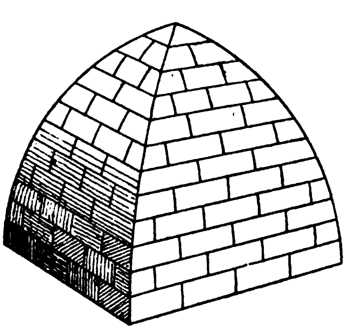


Fig 13.

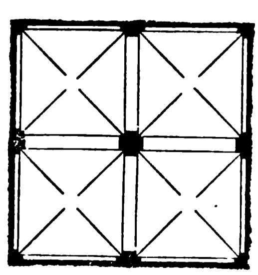


Fig. 14.

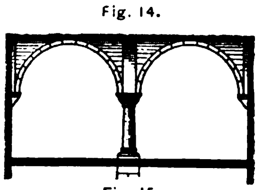


Fig. 15.

be conical or conoidal. The groin-line is straight on the plan. Its curve is elliptical if the composing vaults are conical; otherwise it is indefinable but approximates to elliptical. Fig. 10 is a quarter plan, and Fig. 11 a half section of a domical vault composed of conical, or straight-sided conoidal vaults. Fig. 12 is a half section of one composed of convex-conoidal vaults.

c. The so-called "cloistered arch" or square dome (Fig. 13) is composed of four parts of equal barrel-vaults. It is the reverse of the groined vault.

d. A square room may be covered by four quadrilateral vaults, all springing at one of their corners from a central shaft, as in Figures 14 and 15, from the Castle of the Wartburg. Such vaulting is quite common in crypts.

II. *For covering an oblong compartment.*

a. In Welsh, or underpitch vaults, the composing vaults are generally cylindrical. Both spring from the

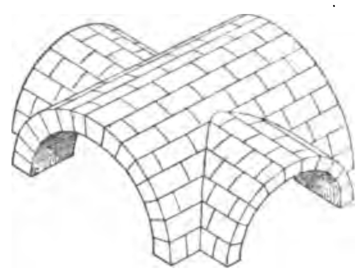


Fig. 16.

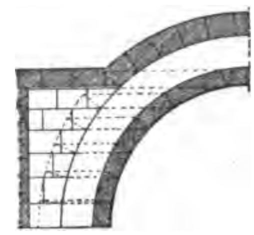


Fig. 17.

same level, but the transverse or side vaults are narrower than the main, and do not completely intersect it (Fig. 16). The groin-line on the plan is a hyperbola. In this case, as in most others where the side vault is narrower than the main, the joints are spaced off on the main, and those of the side are determined by projection, horizontally, from them, as in Fig. 17. The result here is that while the *voussoirs* of the main vaults are all equal, those of the side increase in width as they rise; and the side vault is thinner than the main vault.

Welsh vaults are occasionally found in Romanesque work, and are common in Renaissance. They can be produced by the intersection of a barrel-vault, cylindrical, elliptical, or pointed, with transverse pointed, elliptical, conical, or conoidal vaults; but examples of such constructions, if they exist at all, must be very rare.

b. In stilted vaults the composing vaults are cylindrical, but the transverse is narrower than the main and springs from a higher level, so that the intersection may be complete and both ridges on the same level.

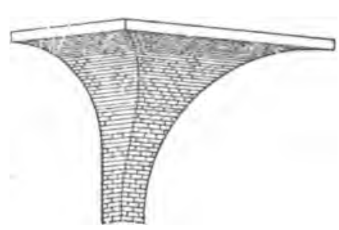


Fig. 18.

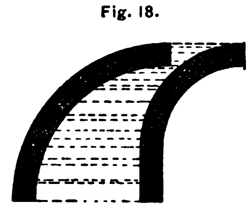


Fig. 20.

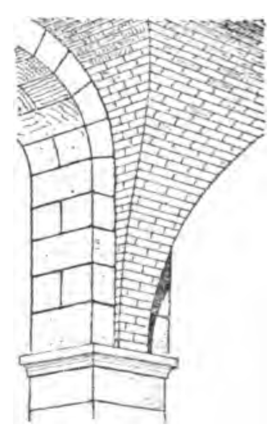


Fig. 19.

The groin-line is of double curvature. Stilted vaults were used by the Romans on a grand scale, to cover the halls of their baths (Fig. 18). They also appear in French Romanesque (Fig. 19). The Romans built them of brick and concrete. When they are of stone the planes of the joints of the vertical portion, or stilt of

the side vault, will be inclined ; and those of the curved portion will not radiate from the axis, (See Fig. 20) or, the joints of the main vault may be level up to the plane from which the transverse vault springs, and those of the stilt will be level also.

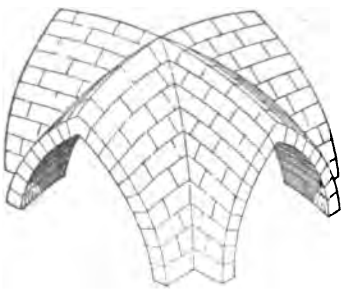


Fig. 21.

c. When the main vault is cylindrical and the transverse pointed, both ridges are on the same level.

This is a German Romanesque form of easier construction than Welsh or stilted vaults.

d. When the main vault is cylindrical and the transverse elliptical with its major axis vertical, the groin-line will be straight on plan.

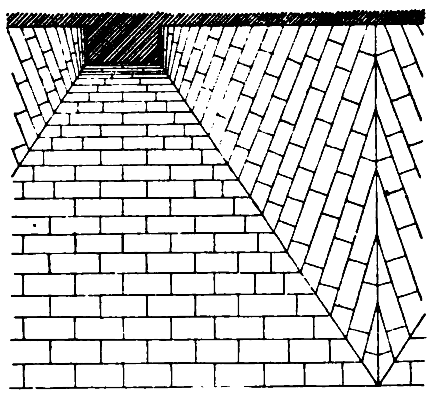


Fig. 22.

e. When the main vault is elliptical, with its major axis horizontal, the transverse is cylindrical, with its radius equal to the height of the main.

f. Both vaults can be pointed and spring from the same level, the transverse being narrower than the main and more sharply pointed so that the ridges may be on the same level. Or, both ridges may rise to the centre (Fig. 21).

g. In a pointed main vault intersected by transverse vaults which are pointed, or double-surfaced, straight-sided conoidal (Fig. 22 is a plan, 23 a transverse section, 24 a longitudinal section) the groin-line is straight on plan. Note the disposition of the joints in the side vaults. The ridges of the side vaults are not straight, but of very slight curvature.

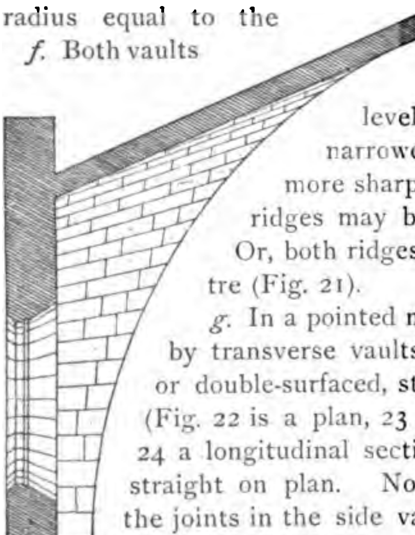


Fig. 23.

h. In segmental vaulting (Fig. 25), the composing vaults may be equal or unequal, and spring from the spandrel of the cross-arch.

i. Of a segmental main vault intersected by a cylindrical transverse vault (Fig. 26), examples occur in French Romanesque.

B. — OBLIQUE VAULTS.

a. With straight axes, composed of equal or unequal barrel-vaults (Fig. 27).

b. An annular vault intersected by a conical vault (Fig. 28). The apex of the cone is the centre of the annulus. The ridge of the conical vault is tangent to the curve of the cross-section of the annulus.

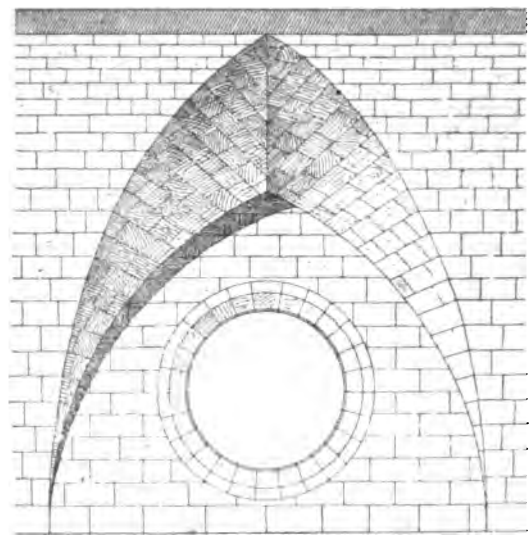


Fig. 24.

The groin-line is slightly curved on plan, but may be made straight by substituting a conoid for the cone.

c. An annular vault intersected by an underpitch vault (Fig. 29). From the church of Notre Dame du Port, Clermont.

d. An annular vault intersected by a stilted cylindrical vault (Fig. 30). This form, and the two preceding ones are found in the French Romanesque churches, the annulus covering the semi-circular aisle which sweeps around the apse of the choir.

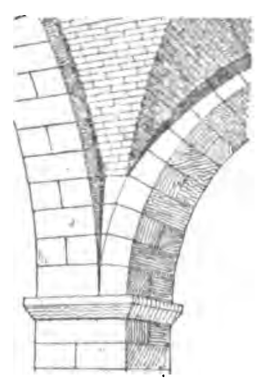


Fig. 25.

Fig. 26.

C. — IRREGULAR VAULTS.

There are many examples of vaults whose surfaces do not conform to any regular geometrical shape. In some cases only the cross arch and the groin stones are cut and properly formed, in others the groin stones only; the rest of the vault being built of rubble, brick, or concrete, apparently shaped by "rule of thumb," and meant to be plastered over.

TRIPARTITE.—These cover a triangular space, and are formed by the intersection of three barrel or three expanding vaults (Fig. 31). They are used, in Romanesque buildings, alternately with quadripartite vaults, over aisles of polygonal apses, as in Figure 32, from Aix-la-Chapelle.

POLYGONAL.

a. The common octagonal vault, generally called a dome (Fig. 33), is composed of eight equal parts of a cylindrical vault.

An octagonal space might be covered by a groined-vault formed by the intersection of four equal barrel-

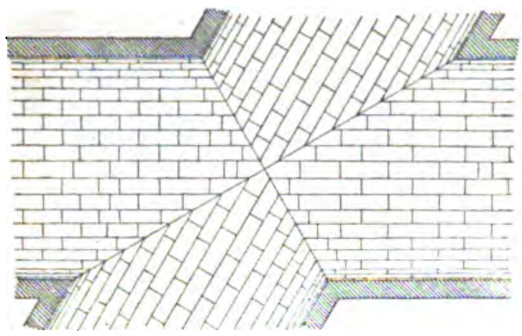


Fig. 27.

vaults, or eight expanding-vaults; but we know of no example of such a construction in solid vaulting.

Figure 34, from Aix-la-Chapelle, is a section of an octagonal brick vault, carrying a pyramidal roof of masonry.

b. Figure 35 is a section of an octagonal vault having

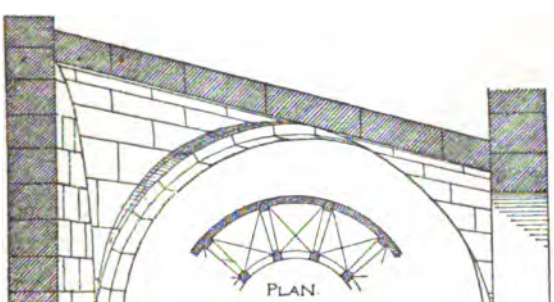


Fig. 28.

each of its sides intersected by an underpitch vault. It is Byzantine work, at Neo-Cesarea, supposed to have been built about the year 375 A. D. The external angles are buttressed.

c. Figure 36 is a section of a structure which exter-

Fig. 29.

nally is an octagonal-vault, and internally is composed of eight spheroidal vaulting-cells separated by bands which are portions of the dome out of which we may conceive the cells to have been scooped. It occurs in the building known as the Temple of Venus at Baiæ, the date of whose construction is placed about the year 100.

d. Vaulting of a decagonal room with a central shaft. From the crypt of the chapter-house of Worcester Cathedral. In the quarter-plan (Fig. 37) G is a groin-

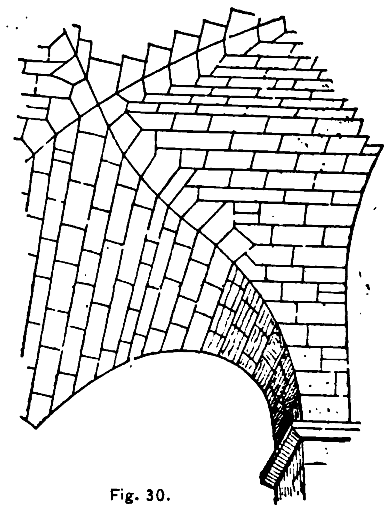


Fig. 30.

line, R the ridge of side vault, and the dotted line is the main ridge. Outside of the main ridge the construction is the half of an annular-vault intersected by

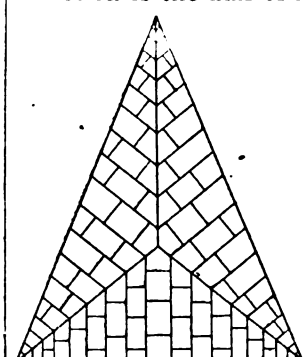


Fig. 31.

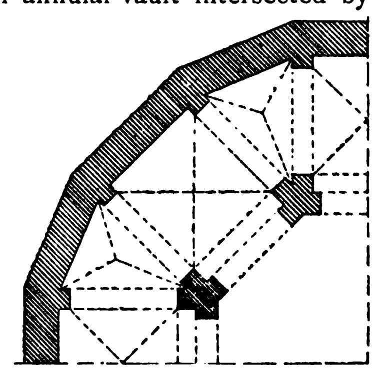


Fig. 32.

ten underpitch pointed vaults; inside there are ten groins whose angles are acute at the springing, but rapidly widen as they ascend, dying out in the surface

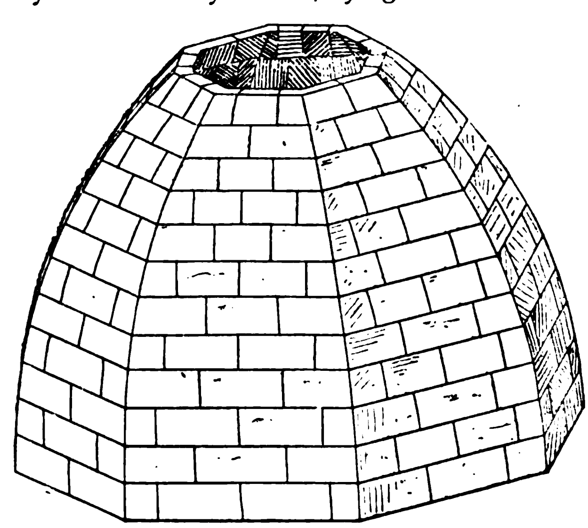


Fig. 33.

of a part of the annulus which is within the main ridge. Figure 38 is a perspective view. The half-round moulding is transverse, that is, in the plane of the cross-section of the annulus.

FAN-TRACERY VAULTING.

THIS is a variety of solid vaulting occurring very frequently in the later period of Gothic architecture, especially in England. Just preceding it we find the

same forms in rib-vaulting; but in the fan-tracery vaults there are no constructive ribs. The surfaces

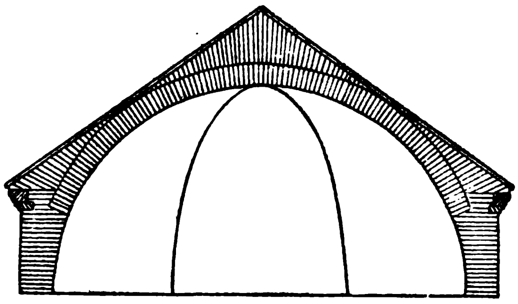


Fig. 34.

are covered over with mullions and tracery-bars enclosing panels, but these are merely ornamental. We

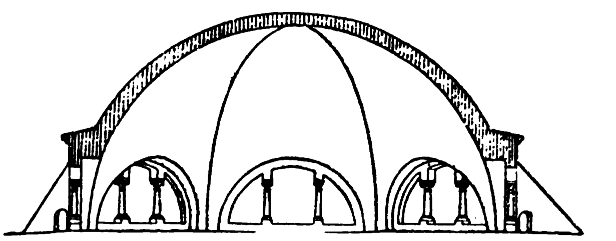


Fig. 35.

cannot here give any illustrations showing the architectural effect of these elaborately finished ceilings,

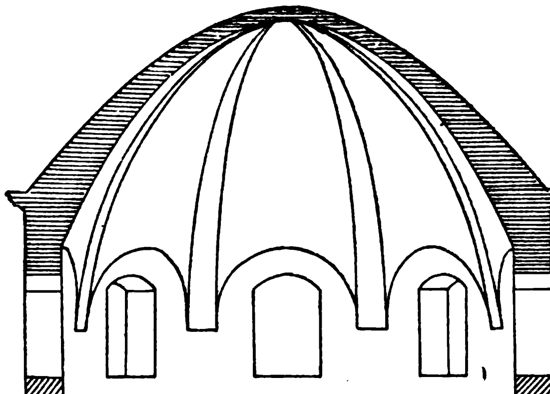


Fig. 36.

but must confine ourselves to indicating the forms in which they occur. The great examples, such as Henry the Seventh's Chapel, in Westminster Abbey, King's

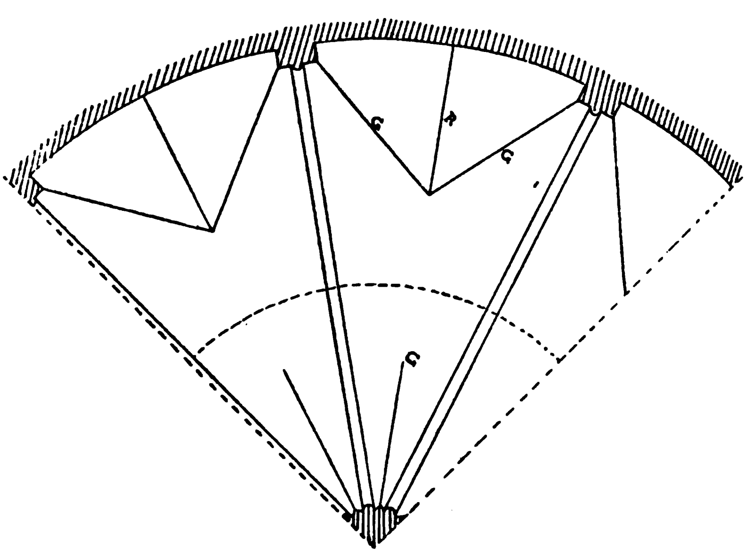


Fig. 37.

College Chapel, Cambridge, St. George's Chapel, Windsor, etc., are doubtless familiar to our readers.

There are two kinds of fan-tracery vaults, viz.: Pyramidoidal, and Conoidal.

1. Pyramidoidal. — A space or compartment may be covered, or partly so, by two halves of an inverted concave pyramidoid, set opposite to each other, so that their bases come into contact on the ridge. The bases may be square, hexagonal, or octagonal; or, indeed, theoretically, may have any number of sides. So far as examples are concerned we might confine our attention to the octagonal, as it is almost the only one in use, and even that is not common. We will,

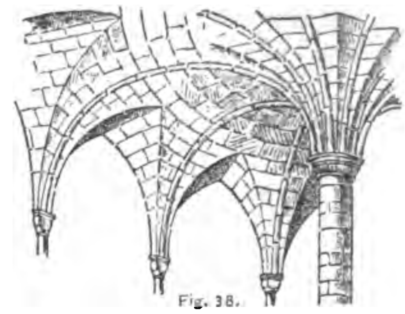


Fig. 38.

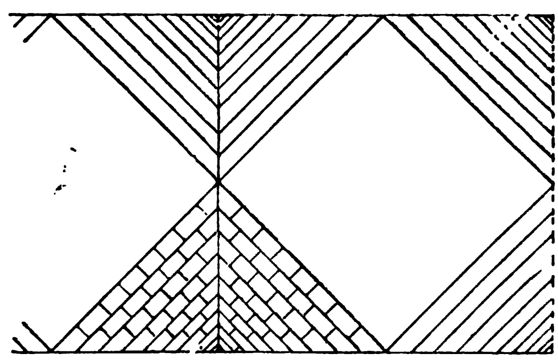


Fig. 39.

however, take a look at the possible forms, if only for the purpose of showing the objections to them, and thus, perhaps, getting at the reason why they were not used.

a. Base square. If the two halves of a concave pyramidoid with square base be set opposite each other so that their *sides* touch on the ridge, the space is entirely covered, and we have simply ordinary quadripartite vaulting. But if the bases touch each other at the corners, as in Figure 39, only half the space is covered. The portion of the ceiling thus left vacant is called the ridge-lozenge. To complete the structure this must be filled by a flat vault, slabs of stone, ribs and panels, or some other device, as it is the key of the vault. The great size of

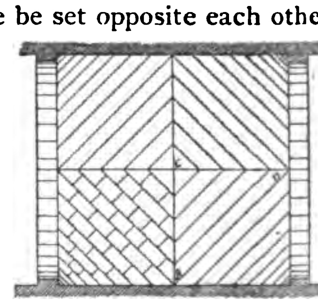


Fig. 40.

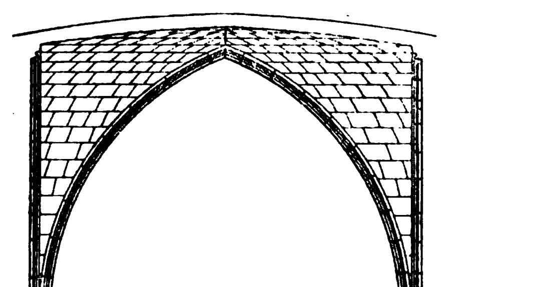


Fig. 40a.

the ridge-lozenge is a serious objection in this case and probably accounts for the rejection of the form.

Here, if a digression may be allowed, it may be inter-

esting to consider, for a moment, what might have been done, and to wonder why it was not. If the surfaces of the pyramidoids in Figure 39 be portions of a cylinder whose diameter is not less than the diagonal of the square space to be covered, they may be continued beyond the line A B in Figure 40, to the centre C, thus obliterating the ridge-lozenge and forming a domical vault covering the entire space. The same form may be obtained by the intersection of two equal

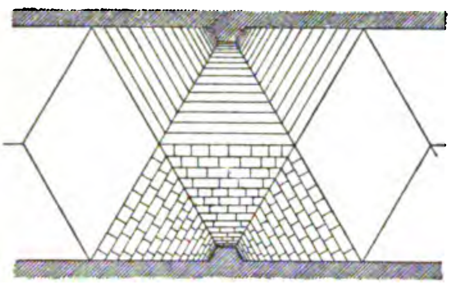


Fig. 41.

cylindrical or pointed vaults whose axes are the diagonals of the compartment. Two of the groin-lines run transversely from wall to wall, the others are against the walls. They intersect, not at the ridge, but at the springing. If the surfaces are cylindrical the groin-lines will be of elliptical curvature, which, æsthetically, might be objected to, as they necessarily form a pointed arch, and pointed elliptical arches are not agreeable to the eyes of some persons. By making the groin-lines circular, however, the surfaces would become elliptical, which would be unobjectionable. The introduction of a cross-arch, or band, would take away the unpleasant

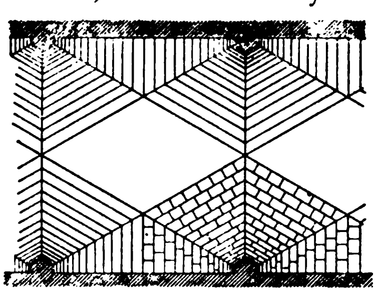


Fig. 42.

effect of a groin *line* running transversely. Thus we should have a form of vault, shown in the section (Fig. 40 a), which would be of easy construction, and well adapted for receiving the ornamental treatment characteristic of fan-tracery vaulting; and one which would readily have yielded to the modification required by the preference for the depressed, or Tudor, arch prevailing in the sixteenth century. It seems strange

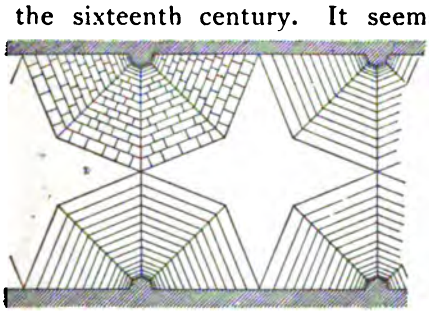


Fig. 43.

that it was not adopted, for this very form is found in rib-vaulting of the fifteenth century (See Fig. 104 hereafter), and must have been familiar to the designers of fan-tracery vaults.

b. Base hexagonal. The halves may meet by the sides (Fig. 41), or the points (Fig. 42). In either case the ridge-lozenge occupies one-third of the space.

c. Base octagonal. The halves may meet by points (Fig. 43), leaving a star-shaped ridge-lozenge which

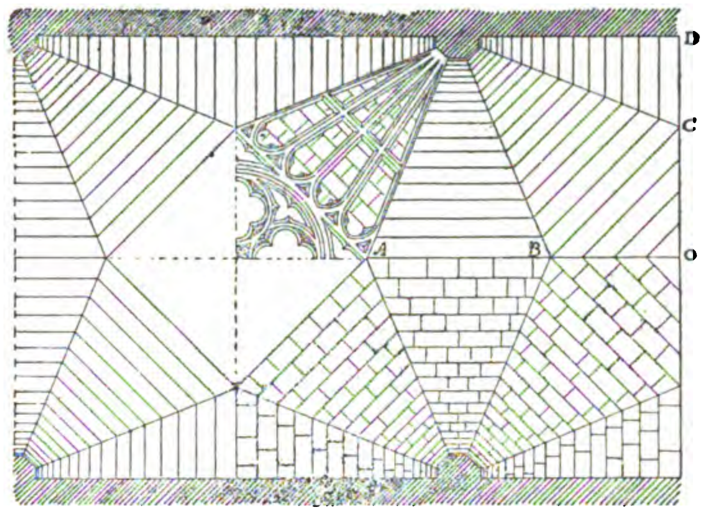


Fig. 44.

occupies about three-tenths of the space; or by sides (Fig. 44), which leaves a square ridge-lozenge that covers only about one-sixth. This latter is a practicable form.

If those surfaces of the pyramidoids whose axes are oblique to the compartment be continued on to the centre, as in the right-hand end of Figure 44, the ridge-lozenge will be obliterated and the construction simplified, while the ornamentation may be precisely the same as if the ridge-lozenge were retained. The ridges of such a vault would be level from A to B, and from C to D, rising from B and C to O. The form is common in rib-vaulting. (See Fig. 105 hereafter).

II. Conoidal.

a. For covering a square space. The half conoids

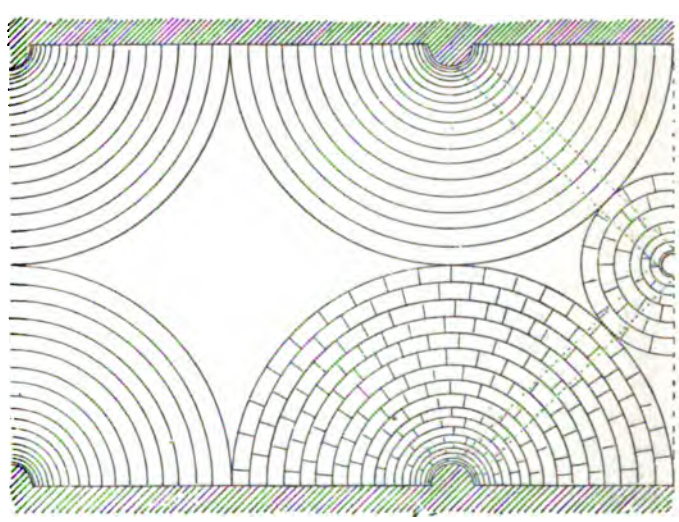


Fig. 45.

have their bases tangent to each other at the ridge and against the walls. (Fig. 45).

b. For covering an oblong space. The conoids intersect at the sides. (Fig. 46).

In conoidal vaulting we often find pendents. These are entire conoids. If central, they partially cover the ridge-lozenge, and are sustained by the long key-stones

of rib-arches which are invisible from below. (Figs. 45 and 47). Side pendents are sustained in a similar manner, as shown in Figure 48, the lower part of the arch being visible. The pyramidoids and conoids are sometimes called pendentives.

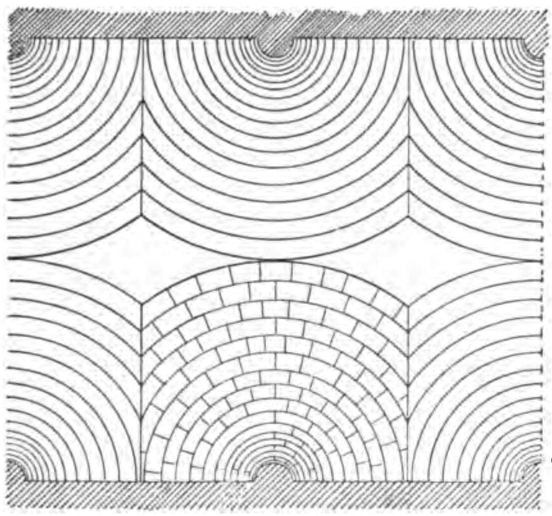


Fig. 46.

RIB-VAULTING.

In fully developed rib-vaulting the surfaces, termed panels, are sustained by a skeleton structure of ribs.

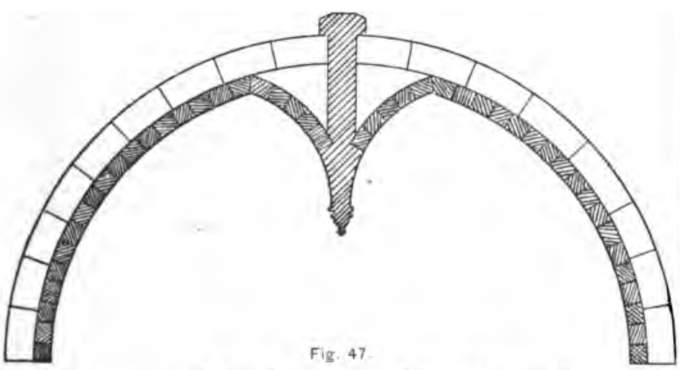


Fig. 47.

The ribs are of hard stone, while the surfaces are usually of lighter material, tufa, brick, pumice-stone, sometimes even of wood. The pieces forming the panels may run straight from rib to rib, in which case the surfaces are either cylindrical, elliptical-cylindrical, conical, or straight-sided conoidal. Or the surfaces may be arched from rib to rib, being then convex-conoidal, or spheroidal. The ribs may be of circular or of elliptical curvature, and may form semi-circular, pointed, elliptical, three-centred or four-centred arches. They are laid, as it is evidently proper that they should be, in vertical planes; that is to say, they are straight on the horizontal projection. There are occasional exceptions, but in these the panel on one side prevents the rib from falling sideways, and the two mutually sustain each other.

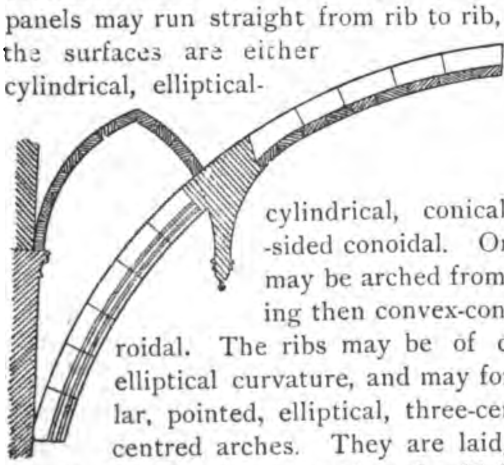


Fig. 48.

It is sometimes stated that the first step in the development of the rib system of vaulting is the thickening of the cross-band in barrel-vaults, and making it an independent arch, with the vaulting surface above it. But such a rib, while it may add to the stiffness of the whole structure, and while it is certainly a pleasing break in the monotony of a long barrel-vault, does not, in Romanesque work, carry the vault, which must be thick enough to stand by itself, and is just as well able to do so over the cross-arches as between them. And as a matter of fact, true ribbed barrel-vaults, in which the pieces that form the surfaces are supported at their ends on the backs of the ribs, are very rare until after the invention of compound rib-vaults. We know of but one or two Roman examples, and of no Romanesque. We must look elsewhere for the beginning of the Mediæval rib system. We shall find the first step to consist in the substitution of a square-cornered arch for the groin-stones, of a compound solid vault, as in Fig. 49, from San Ambrogio, Milan. Here, there is a great advance in ease of construction.

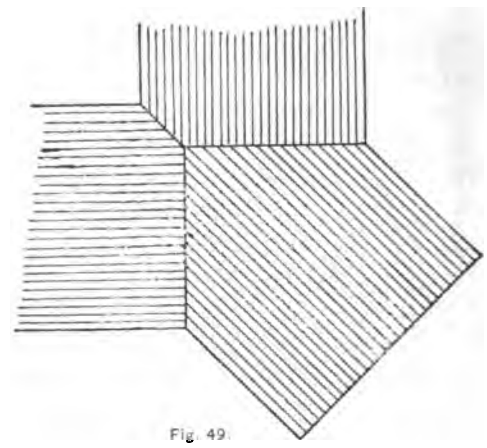


Fig. 49.

The shaping of the groin-stones in a Roman vault is quite a problem in stereotomy. The springer has seven surfaces, and every other stone, up to the key, which is still more complex, has eight, viz.: two cylindrical soffits, two cross-joints in vertical planes, two planes of the leading joints on the bottom, and two more on the top, as in Fig. 50. Besides this, no two stones are alike, as the groin-angle varies continually, increasing as it rises. But the groin-arch substituted is a comparatively simple thing, and all its voussoirs may be cut from one pattern. We now have solid vaulting with groin ribs. This is not properly rib-vaulting, because the vault is still thick enough to form an arch, and rests upon an auxiliary support only at the groins. Indeed, the stability of such vaults is often quite independent of the groin-ribs, which are then rather ornamental than useful. The ruins of the Bishop's Palace,

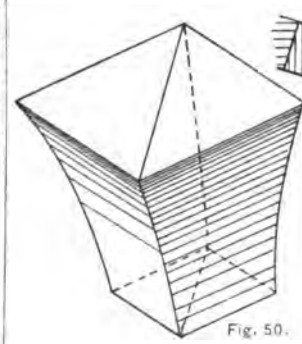


Fig. 50.

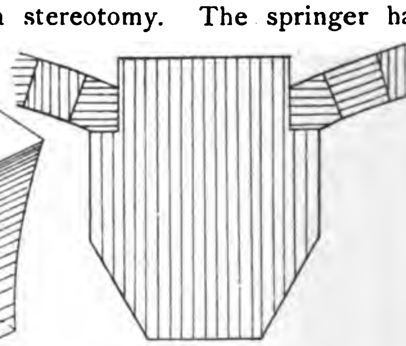


Fig. 51.

at Lincoln, present a case in which the ribs have fallen away, leaving the vault, which is built of rubble, quite sound. There are, however, some small rib-vaults, having only groin and wall ribs. The latter are not necessary to the construction, as the ends of the surface-pieces might be let into the wall; but the former are. There are also vaults with *transverse* and wall-ribs only, but they are of a much later date than those we have just mentioned, and of a different shape.

The name "groin-ribs" is usually given to those which lie at the intersections of the main vault with the transverse, and therefore cross the compartment diagonally. Strictly used it should be applied to any rib which carries two panels that are not portions of the same surface, but make an angle with one another, as in Fig. 51, which may occur on a transverse rib, if the panels are spheroidal, or if the vault is domical. We shall use the term in the ordinary sense.

The next step, undoubtedly, was the conversion of the heavy cross-arch of the Romanesque vaults into

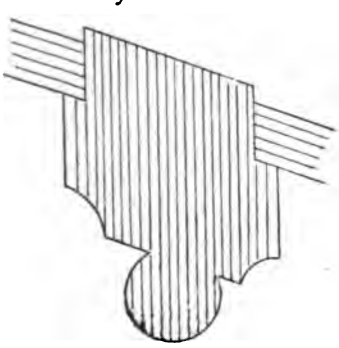


Fig. 52.

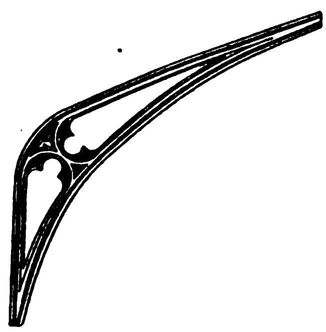


Fig 52 a.

the light transverse rib of the Gothic system. This was a slow process. For a considerable time after the introduction of the groin-rib, the cross-arch remains, somewhat reduced in size, lightened in effect by mouldings, and often in substance by being made compound, but still two or three times as large as the groin-rib. This relation between the two, however, prevails mostly in France, Germany, etc., but is rare in England. On the continent it continues almost until the Renaissance.

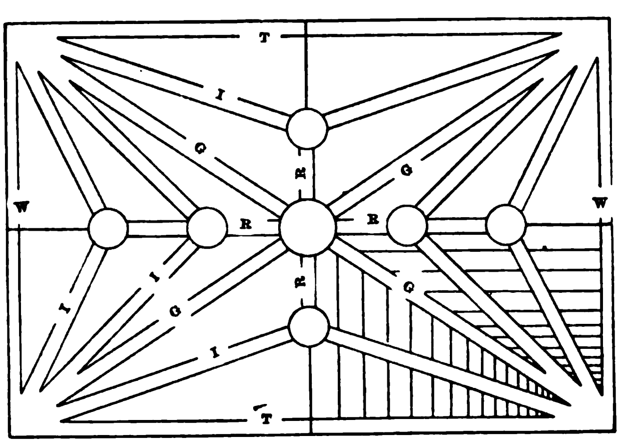


Fig. 53.

In England the transverse rib is nearly or precisely of the same size and section as the groin.

Then follows the wall-rib, which shows half, or a little more, of the section of the transverse, and is built into the wall. It is really the transverse rib of the side vault.

The next is the intermediate rib, which lies between the groin and transverse, or groin and wall. If it lies in a surface which is continuous from the groin-rib to the transverse, or wall-rib, its section must be distorted,

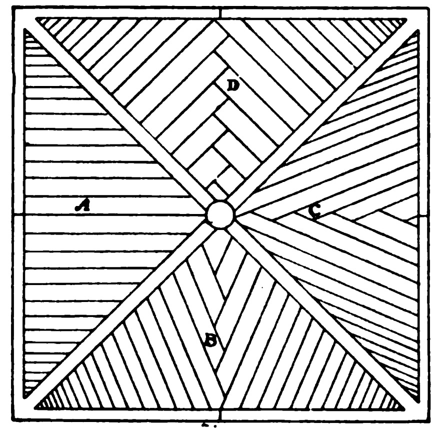


Fig. 54.

as in Figure 52, and variable, because the lines of jointing, or rather the elements of the surface, strike it higher up on the side next the groin than on the other; or else the rib must be curved sideways. Both difficulties are avoided by making the panels spheroidal, in which case the intermediate is, strictly, a groin-rib.

With the intermediate comes the ridge-rib. Its use is often said to be merely to conceal the somewhat awkward interlocking of the panel pieces when the joints are not parallel to the axis. This, however, is a mistaken view. The ridge-rib was at first a structural, not an ornamental piece. Its function is to connect

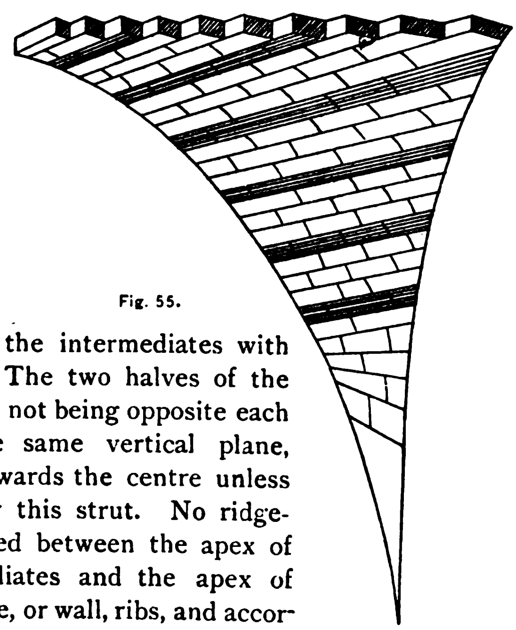


Fig. 55.

the apex of the intermediates with the centre. The two halves of the intermediate, not being opposite each other in the same vertical plane, would fall towards the centre unless prevented by this strut. No ridge-rib is required between the apex of the intermediates and the apex of the transverse, or wall, ribs, and accordingly in early examples none appears in that position.

Liernes, or cross-ribs, are short pieces running from one rib to another, following the form of the panel, the curvature of which they do not affect. They lie underneath panels already formed by other ribs. This is the rule, but there are some exceptions. Ordinarily they serve no practical purpose, except perhaps to brace the skeleton structure; but in some cases they are continuations of the groin-ribs, and then are necessary to the completion of the rib-arch.

Occasionally, in late Gothic work, as in St. Mary's Church, Warwick, groin and transverse ribs are traceried. Fig. 52, a.

Figure 53, is a plan of a fully developed rib-vault; and the following table gives the names and positions of the various ribs.

POSITION.	ENGLISH NAMES.	FRENCH NAMES.	MARKS ON PLANS.
Diagonal.	Groin.	Croisee d'ogive.	G
Across the main axis.	Transverse.	Arcs doubleaux, or Nervures.	T
Against the walls.	Wall.	Formerets.	W
Between the groin and transverse, or groin and wall.	Intermediate.	Tiercerons.	I
At ridges.	Ridge.	Liernes.	R
From one rib to another.	Liernes, or cross.		L

Ridge angles without ribs are indicated on the plans by single lines.

At the points where ribs meet we often find keystones, called bosses. They receive the ends of the

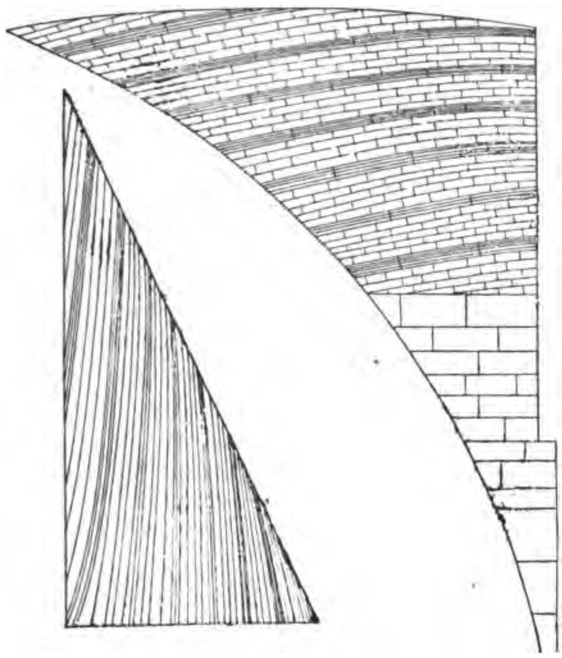


Fig. 56.

ribs, and do away with the necessity of mitreing the mouldings. Their lower ends are richly carved. At centres, bosses are sometimes moulded, the mitres being cut on them, and there is only a bit of leaf-work covering the intersection of the soffit mouldings.

SECTIONS OF RIBS.

Ribs are generally moulded by chamfering, by coves, or by combinations of rolls, fillets hollows, etc.

JOINTS.

The joints of the panels may run in almost any direction, and are often quite irregular. The most common systematic methods of laying them out on the plan are shown in Figure 54. In the part A, they are parallel to the axis; in B, perpendicular to the line that bisects the lower angle of the panel; in C, perpendicular to the line bisecting the lower angle of the opposite panel; in D, perpendicular to the groin rib. If they are kept level, A is applicable only when the ridges are level, and B, C, and D to domical vaults. But in A, they may rise from the transverse, or wall, to the groin rib, making a domical vault. In B and D they may fall, except a few at the bottom, and the ridge may be level, as in Figure 55, from the cloisters of Westminster Abbey. In C they must rise. Figure 56 gives a plan and elevation of a panel from the nave of Westminster Abbey, banded with occasional courses of dark stone, which is not common.

In the early examples, and in many late ones, the ribs are few, only groin, transverse, and wall; and each one starts from the spring with its full section, and is often supported by its own independent shaft as in Figure 57. When intermediates are added such an arrangement is clumsy, and therefore the ribs are bunched together at the springing, each starting with only a part of its section, as in Figure 58. As they rise the sections increase, and become full at the point where the ribs separate and the panels begin. Up to this height the work is solid, and is called the springer. It is a corbel bonded into the wall sustaining the ribs. Its joints are often horizontal, Figure 59. In ruins it is generally seen standing after the ribs have fallen. On the plan, Figure 53, it will be observed that the groin-rib and the inner intermediate of the side vault separate from each other farther inward, and, therefore, at a higher point than from the other ribs, and thus attain their full section sooner on one side than on the other. This often occurs, but may be considered awkward. It is remedied by retiring these two ribs somewhat at the springing, or by advancing the others; or, more effec-

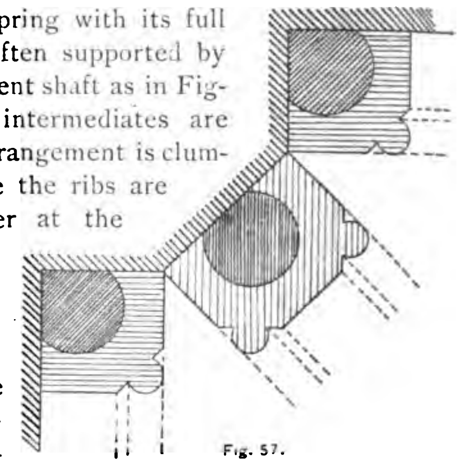


Fig. 57.

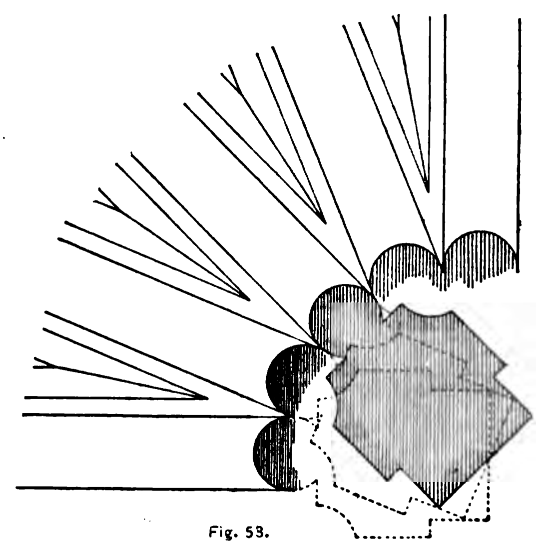


Fig. 58.

tually, by making all of the ribs of the same curvature up to the top of the springer.

Sir Gilbert Scott states that it was not uncommon for stone springers to carry wooden ribs. He finished the nave of Chester Cathedral in that manner. The vaulting of the great octagonal central space of Ely Cathedral is so constructed; but this probably would not stand if the ribs were of stone.

The student will find a very full discussion of the methods of laying out ribs in an article by Prof. R. Willis, "On the Construction of the Vaults of the Middle ages," in the Transactions of the Royal Institute of British Architects, Vol. I, Part II, 1842.

Although it is not a part of our subject, it may not be amiss to say a few words in regard to the *thrust* of

vaults, and the means of resisting it. In the case of a barrel-vault, as it pushes against the wall alike at all points, (if it exerts any thrust, which some do not,) they must be thick enough to resist it; or there may be half vaults acting as flying buttresses, as in Figure 3. The

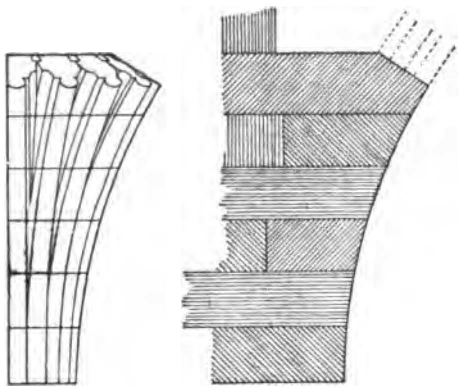


Fig. 59.

great Roman groined-vaults, and many of their barrel-vaults, being built of bricks, and concrete with mortar which is as hard and strong as the other materials, are not amenable to the mechanical laws of the arch, and need no abutment, but only a sufficient vertical support. A symmetrical stone groined-vault, whether solid or ribbed, exerts its thrust in the plane of the transverse section. In Romanesque work the walls are of sufficient thickness to afford a proper resistance. In the Gothic system the thrust is opposed by buttresses, and the walls may be dispensed with so far as the vault is concerned. The flying-buttress, if its function be, as many suppose, to convey the pressure of a nave-vault as directly as possible to the aisle wall and its buttress, is never, we believe, scientifically located, that is to say, it is not in the line of pressure. If it were, it would in most cases pass through the aisle-vault. It is always of course above the aisle vault; in early work between it and the roof; in the middle and later periods above the roof. It is sometimes a stone strut, supported by a half arch; and, more commonly, a half arch covered by a coping. In the latter case its function is to resist the thrust of the vault by its own thrust at the crown, which is exerted horizontally and distributed over a considerable vertical space of the wall or pier which carries the vault. Its outward thrust is resisted by the pier, pinnacled or not, which rises up from the aisle buttresses. In many cases it is applied to the clerestory wall at a point above that at which the line of pressure comes out; often at the top of the wall.

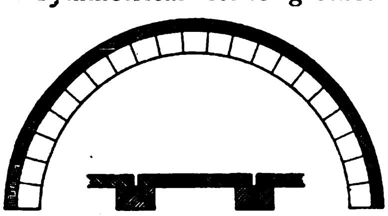


Fig. 60.

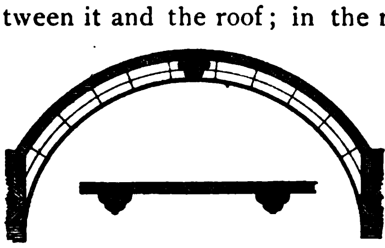


Fig. 61.

As to the method of laying vaults, those that are solid require strong centering, able to carry their weight until they are finished. Rib-vaults require heavy centreing only for the ribs. The panels, if each course is in a single piece, need no centres; if they are cross-jointed, or if spheroidal, only short narrow centres for each course, or two or three together, which may be supported on the scaffold; and only one set is necessary, as they can be used over and over again for the different panels. Cylindrical panels, however, if wide at the top, as when only groin and transverse ribs are used, must be thick enough to form true arches, and then they are not mechanically complete until the last course, or key, is laid, so that they will need continuous centres. Spheroidal panels are, like a dome, mechanically complete at any point when a course, or ring is finished.

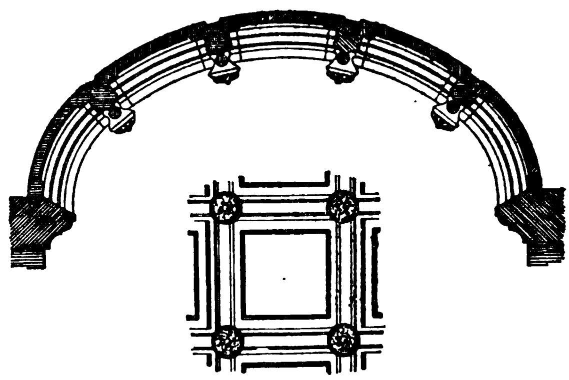


Fig. 62.

Panels are often laid of quite thin stone, and afterwards covered on the back with a layer or two of brickwork, or of concrete, so that the whole vault, when completed, is about as heavy as if it were solid.

We are now prepared to explain and illustrate the leading forms of rib-vaulting.

A. SIMPLE RIB-VAULTS.

Three examples are given.

Fig. 60, from Baths of Diana, at Nismes.

Fig. 61, from hall of Castle Campbell, Scotland.

Fig. 62, a form common in the after Gothic of France.

Another, perhaps the earliest of all, occurs in the Roman Prætorium, at Musmeih, in Syria, erected A. D., 185. (See De Vogue's "*Syrie Centrale*," Vol. 1, Plate 7.)

B. COMPOUND RIB-VAULTS.

We will classify these, as far as practicable, according to the number of cells, or parts, of which they are composed.

1. TRIPARTITE. — These cover a triangular space, which usually occurs in an apsidal aisle, as in Fig. 32.

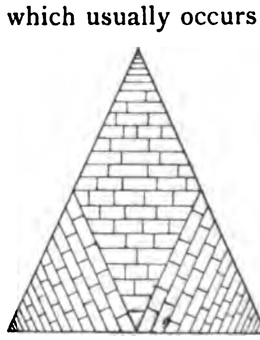


Fig. 63.

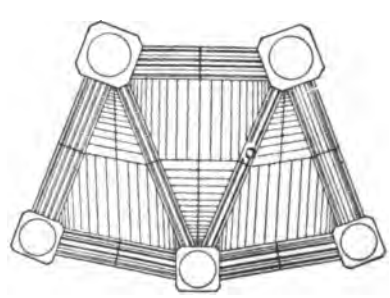


Fig. 64.

The simplest form is that shown in Fig. 65, from the transept porch of the cathedral at Erfurt. It has groin and wall ribs only. There are three cells, each having two triangular panels. Fig. 64 is a plan of the vaulting of a compartment of the inner aisle of the choir of

Notre Dame, Paris. The trapezoidal space, usually covered by a quadrilateral vault, is here covered by three triangular vaults.

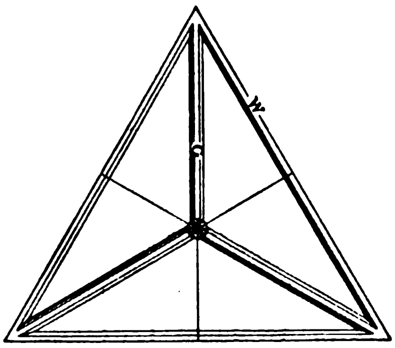


Fig. 65.

The panels of triangular vaults are sometimes arranged as in Figure 63.

2. QUADRIPARTITE. — *a.* Having groin-ribs only. (Fig. 66. Durham Cathedral.) This is not exactly rib

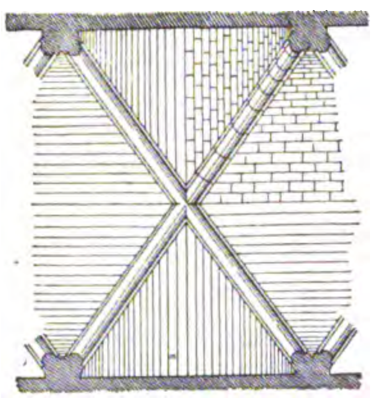


Fig. 66.

and panel vaulting, but rather solid vaulting with groin-ribs.

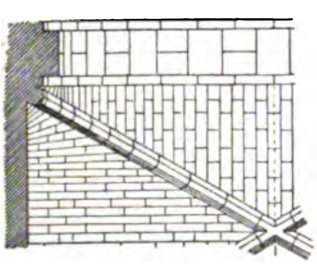


Fig. 67.

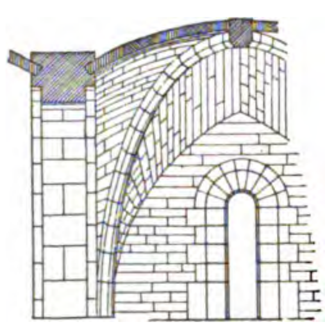


Fig. 68.

b. Groin-ribs and transverse arches. (Figs. 67 and 68. From a church at Gerland, in France.) Both ribs and arches are in this case semicircular.

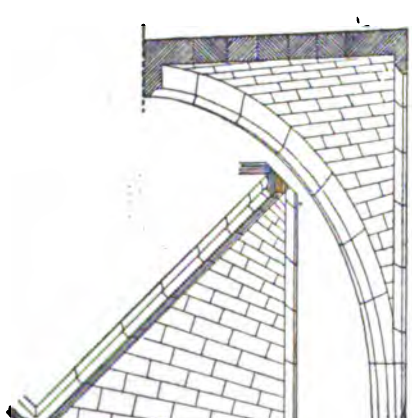


Fig. 69.

c. Groin and wall ribs. (Fig. 69. From B .,ham Abbey.) The groin-ribs are semicircular, the wall-ribs pointed. The ridge descends slightly to the centre.

d. Groin, transverse, and wall ribs. Ridges level. (Fig. 70.) If the panels are spheroidal, the ridges will

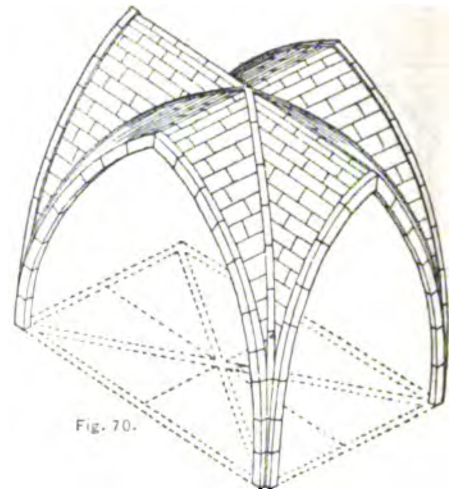


Fig. 70.

be curved. The vaulting of the nave of Cologne Cathedral is of this kind. The transverse ribs are about twice as wide as the groin-rib. The panels of the main vault are spheroidal; those of the side vaults have their joints parallel to the axis. Many of the French cathedrals are vaulted in a similar manner.

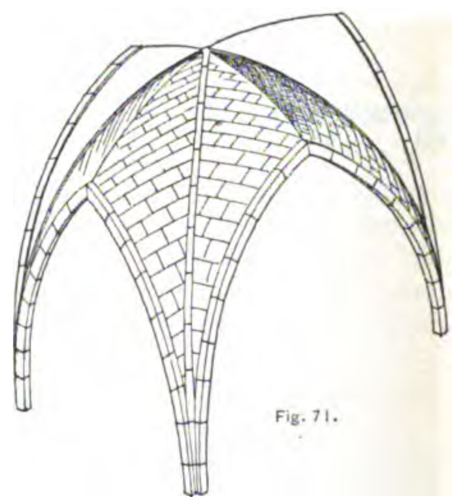


Fig. 71.

e. The same ribs as above, but the vault is domical. The apex of the wall ribs is often lower than that of the main. (Fig. 71.)

f. Welsh vaults. In these the groin-ribs cross each

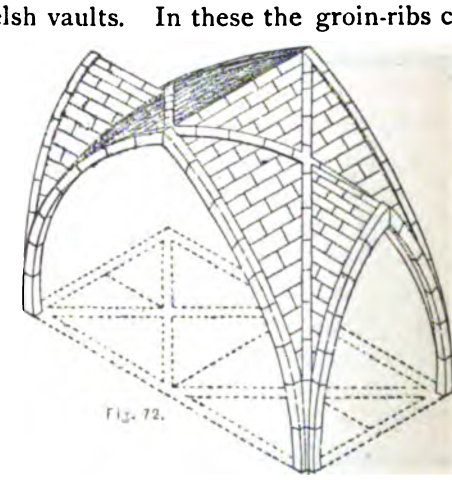


Fig. 72.

other before they reach the main ridge, and are continued from the crossing as liernes. Figure 72, from the cathedral at Ghent. Or they may stop at the crossing,

and be connected with the centre by a lierne rib, as in Figure 73, from the nave of Ulm Cathedral. Welsh vaults are quite common. They occur at Gloucester Cathedral; Melrose Abbey; the church of S. Pantaleon, Cologne; choir of St. Paul's, Antwerp; Brussels Cathedral; Berne Cathedral; Church of St. Castor, Coblenz, etc. In Winchester Cathedral (Fig. 74), the ridge of the side vault descends towards the main. The main ridge is almost invariably level. Figure 75 is a plan of a Welsh vault whose side cells have oblique axes. Two

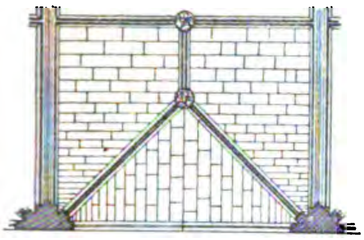


Fig. 73.

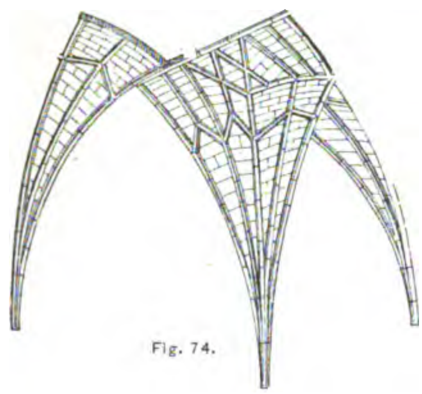


Fig. 74.

compartments are drawn in order to develope the arrangement of ribs.

g. Vaults with groin, transverse, wall and intermediate ribs.

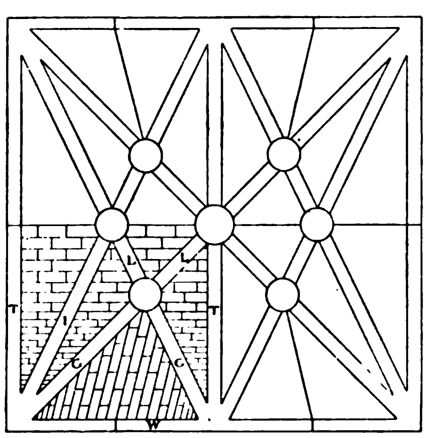


Fig. 75.

ate ribs. (Fig. 53.) Sometimes, as in the nave of Lichfield Cathedral, the transverse ribs are omitted. Liernes are often added, as in Figure 74; and in Figure

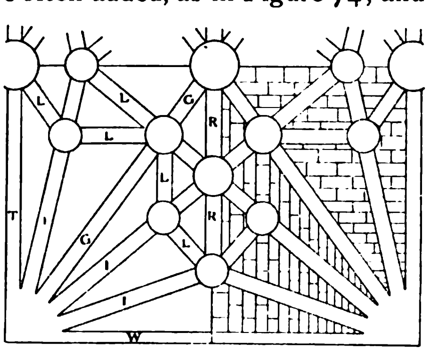


Fig. 76.

76, from the nave of Canterbury Cathedral. Figure 77 has intermediates and liernes: it is from Brussells Cathedral. The ribs are of stone; the panels apparently of brick, spheroidal.

h. Side vaults oblique, reaching to the main ridge, but

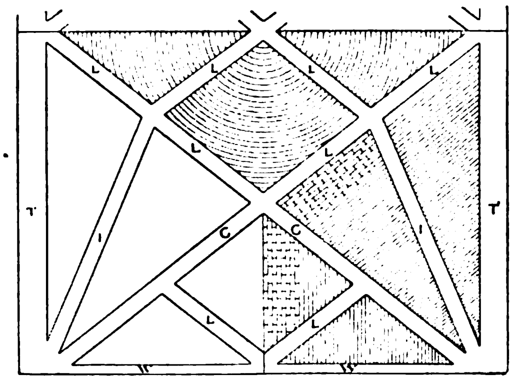


Fig. 77.

not opposite to each other at the apex. Figure 78, from the choir of Lincoln Cathedral. The groin-ribs on each side are met at the centre, not by their other halves

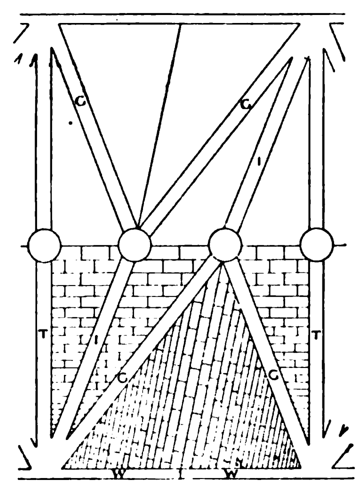


Fig. 78.

from the opposite side, but by an intermediate rib. The intermediate is on one side only of the transverse.

3. Quinquepartite.—*a.* For covering a pentagonal space. These have groin, transverse and wall ribs.

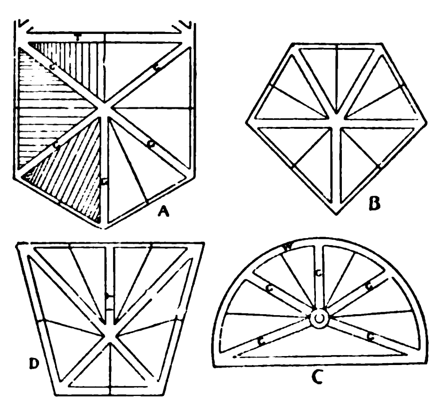


Fig. 79.

Figure 79. A, from the choir aisle of St. Mary's, Lubeck; B, from Bruges and Oppenheim; C, from Noyon, covers a semi-circular space. They occur over the chapels which form the *chevets* of apsidal choirs.

b. For covering a rectangular space. Figure 80, from Luneburg. Three of the wall-ribs, 1, 2, 3, on the plan, are over, or are parts of, arches which open, 1 into the nave, 2 and 3 into the adjoining compartments of the aisle, 4 and 5 are on the aisle wall, and there is a window under each. On this side, what would otherwise be a

single cell is divided by an intermediate transverse-rib into two oblique cells. Figure 80 a, is from the aisles of Lincoln Cathedral.

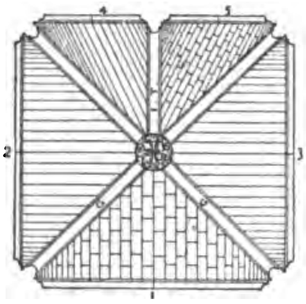


Fig. 80.

c. The above adapted to a trapezoidal space. Figure 79, D, from the choir triforium of Magdeburg Cathedral. Four of the cells are oblique.

4. Sexpartite.—In Figure 81 are plans of vaults with six cells. A is from the chapel at Cobern. B from Treves, covering a space which belongs partly to the aisle and partly to a chapel. C from St. Werner's Chapel, Bacharach; and from Antwerp Cathedral. D from Auxerre, over a compartment of the aisle.

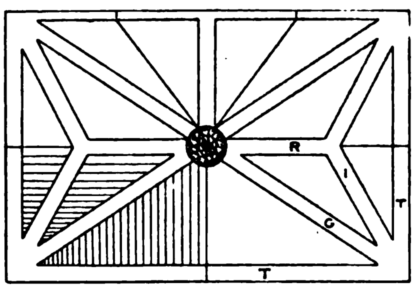


Fig 80 a.

The form commonly known as sexpartite, or hexapartite, is shown in Figures 82 and 83. It is very common in the late Romanesque and early Gothic. Examples may be found at Lincoln, Canterbury, Mantes, Laon, Caen, Dijon, Auxerre, Sens, Notre-Dame-de-Paris, H. Aposteln at Cologne, etc. The side vaults are double and oblique, separated by an intermediate transverse-rib. In early examples the wall-ribs are semicircular; and in many cases they spring from a higher level than the other ribs.

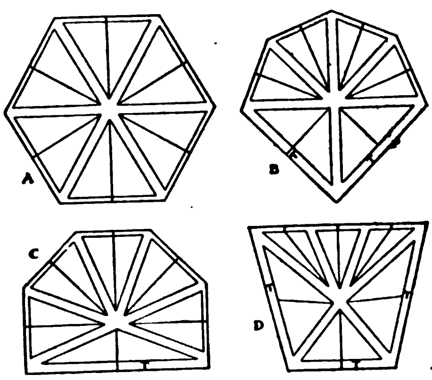


Fig. 81.

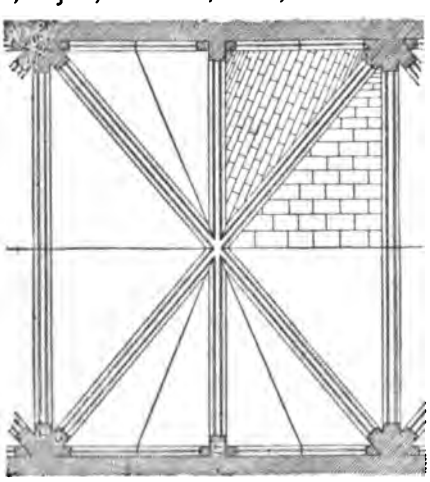


Fig. 82.

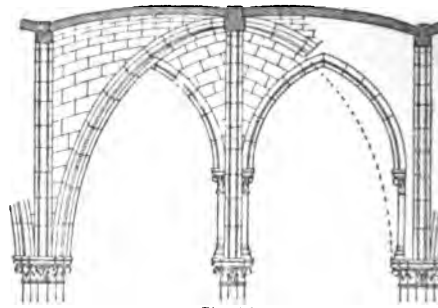


Fig. 83.

5. Septpartite. — Figure 84 shows the common form. It is used over rectangular compartments, in towers and transepts chiefly, which have walls on three sides and an arch on the other. Limburg Cathedral.

6. Octopartite. — *a.* For covering a rectangular space with walls on all sides, as in towers. (Fig. 85.)

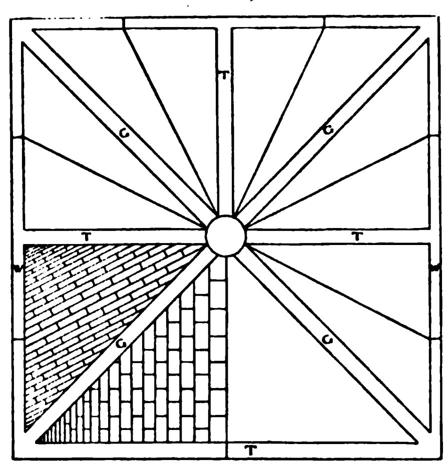


Fig. 84.

There are eight oblique cells. Examples are numerous, as at St. Ived, Braisne; Gelnhausen; Notre Dame de Dijon, etc. Fig. 86 is another, and apparently a unique, form from the central tower of Lincoln Cathedral. The surfaces of the square part in the middle are supported by the groin and transverse ribs of four three-quarters of quadrilateral vaults, which occupy the corners, carried on above the level ridges to the centre. It is an ingenious device for covering a square space with four vaults without a central shaft.

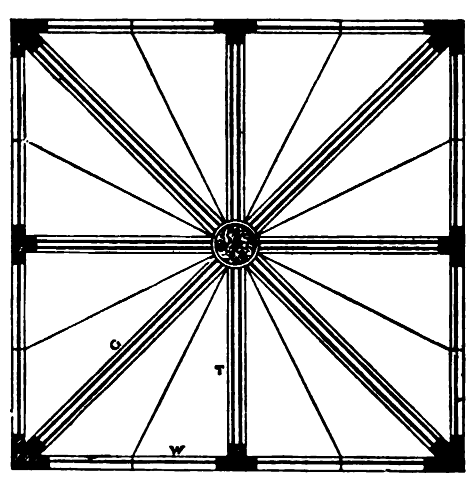


Fig. 85.

b. Fig. 87 is from Notre Dame de Dijon.

Fig. 88 is from Rheims, Laon, and Soissons.

c. For covering an octagonal space, as in chapter-houses, kitchens, etc.

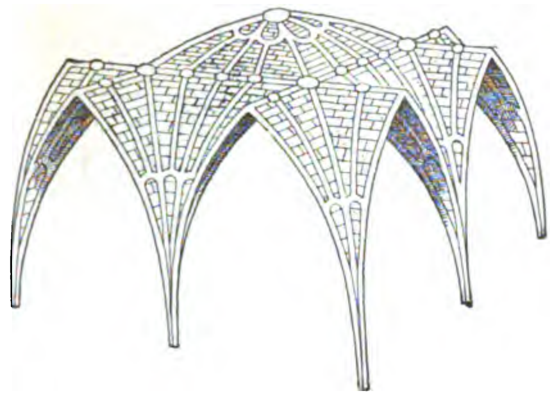


Fig. 86.

I. Fig. 89 is a plan, and Fig. 90 a section, of a vault from Dirleton Castle, Scotland, without cells. It is like

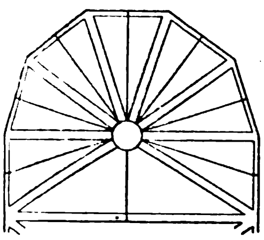


Fig. 87.

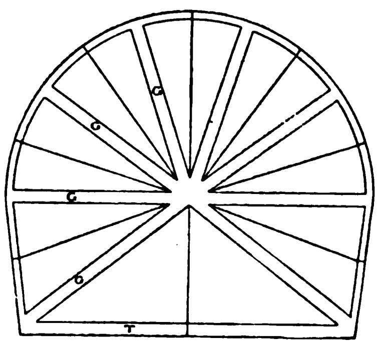


Fig. 88.

the form given in Fig. 33, with ribs in the inner angles, and closed at the top. We suppose it to be really solid

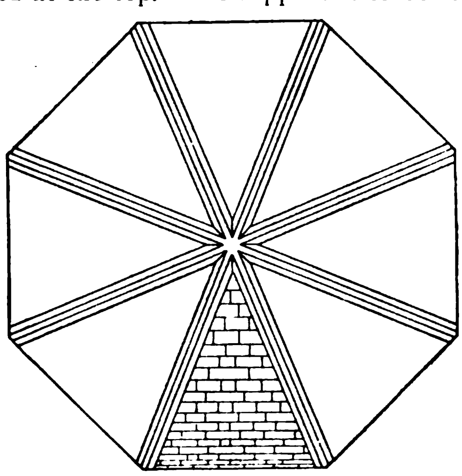


Fig. 89.

vaulting, and the ribs to be only ornamental, though they are heavy enough to be useful, and do away with

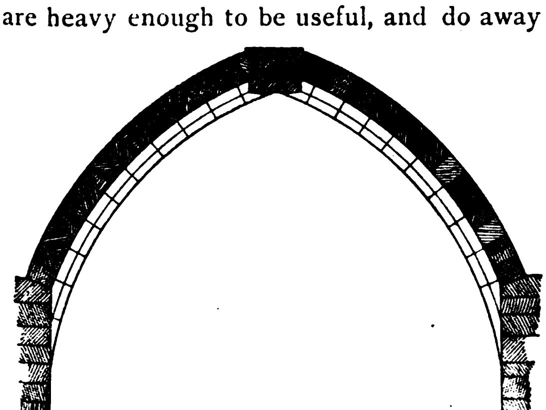


Fig. 90.

the necessity of careful mitreing of the surfaces in the angles.

Fig. 91 gives a section and a quarter-plan

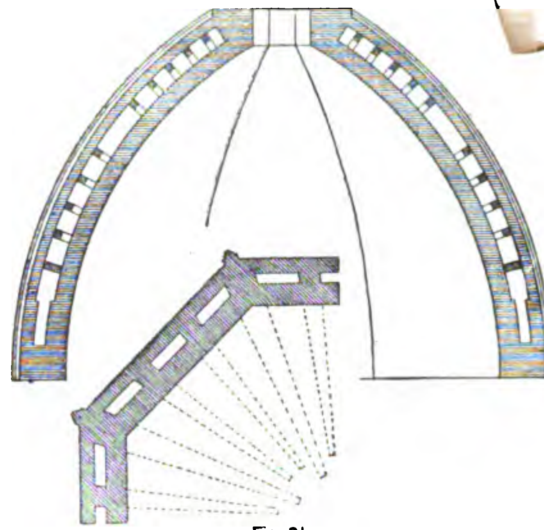


Fig. 91.

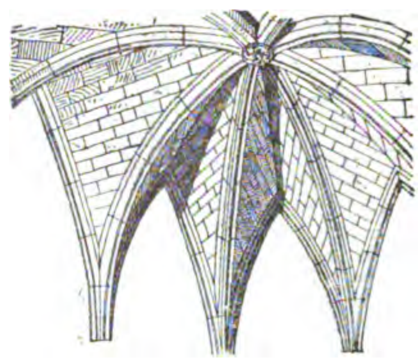


Fig. 92.

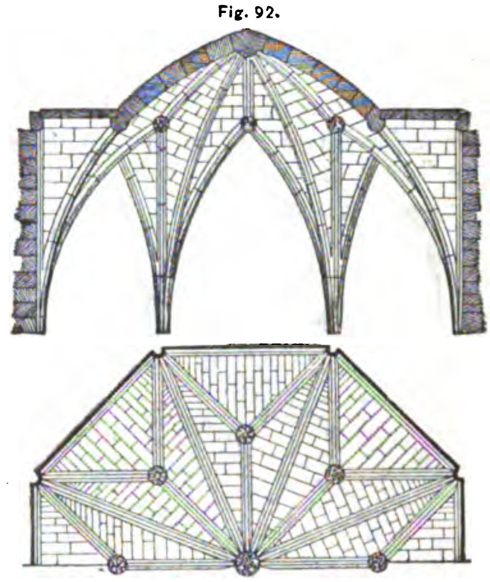


Fig. 93.

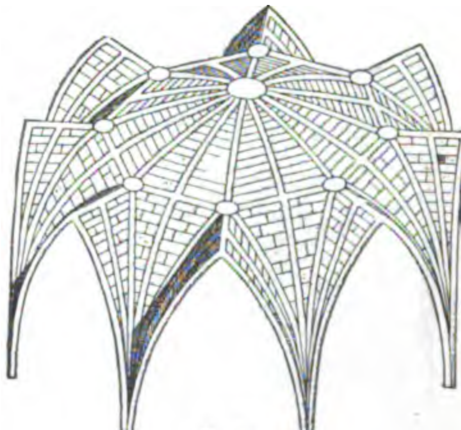


Fig. 94.

called dome of the Duomo at Florence, which is really

a rib-vault, double shelled. The inner shell is not supported by the ribs. The great angle-ribs show on the

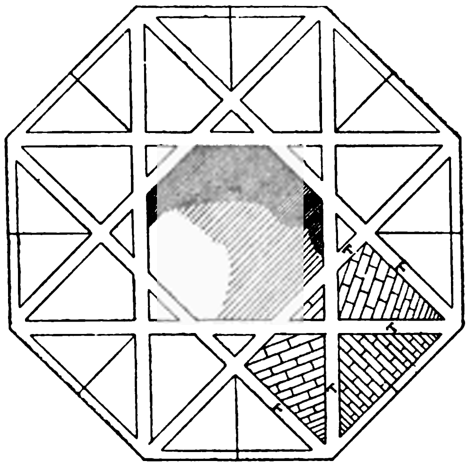


Fig. 95.

outside. Segmental arches are thrown from rib to rib.

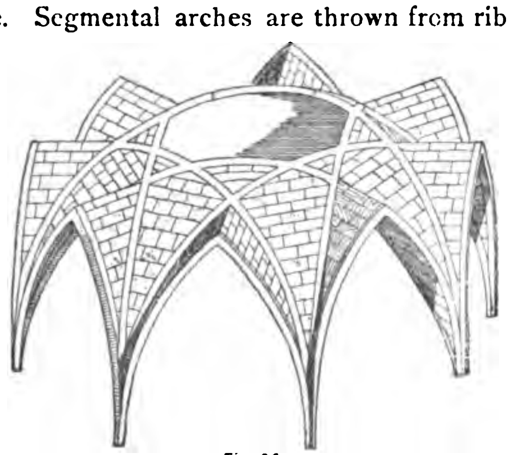


Fig. 96.

II. Groin and wall ribs only, making eight cells. Fig. 92, from Inchcolm Abbey.

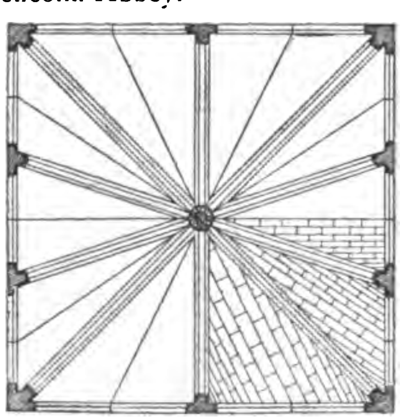


Fig. 97.

III. Welsh vaulting, eight cells. (Fig. 93.)

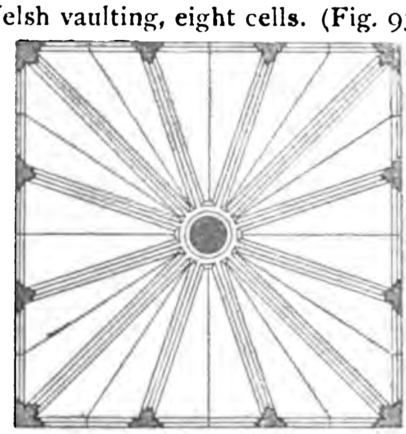


Fig. 98.

IV. Groin-ribs not meeting at the centre, but terminating at the angles of a central octagon. Fig. 94, from the chapter-house of York Cathedral.

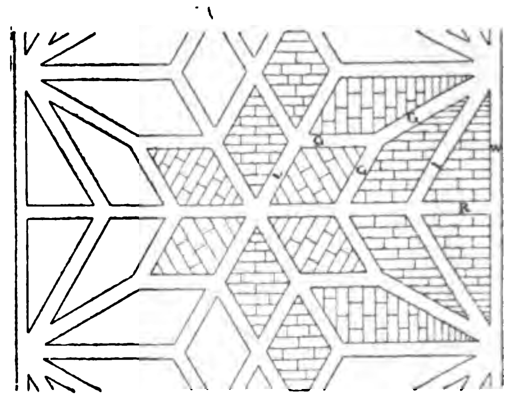


Fig. 99.

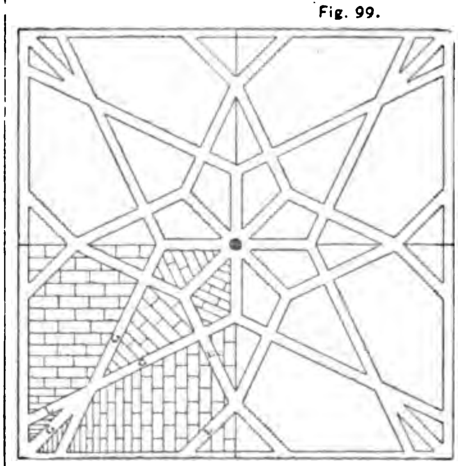


Fig. 100.

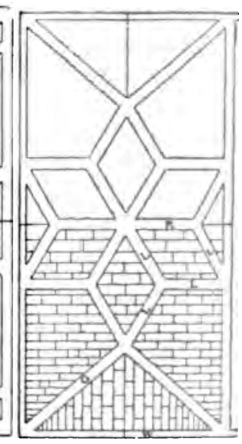


Fig. 101.

V. Eight semi-circular transverse-ribs. Figs. 95 and

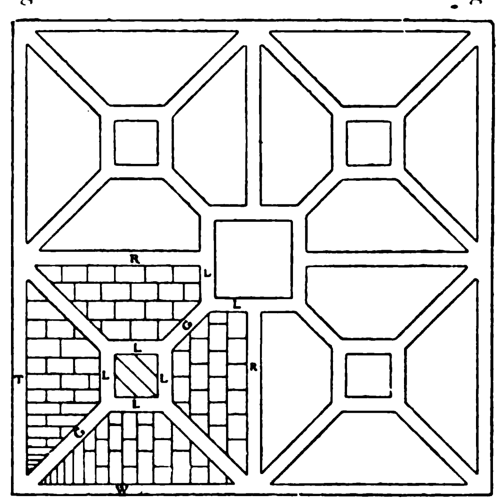


Fig. 102.

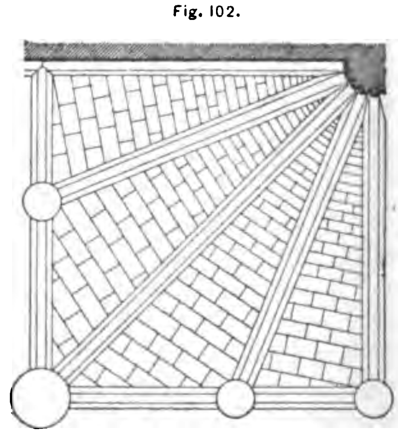


Fig. 103.

96, from the Abbot's kitchen, at Durham. The central space is left open.

7. Decapartite. — Fig. 97 is an example, from the chapel at the east end of the choir of the Cathedral of Auxerre.

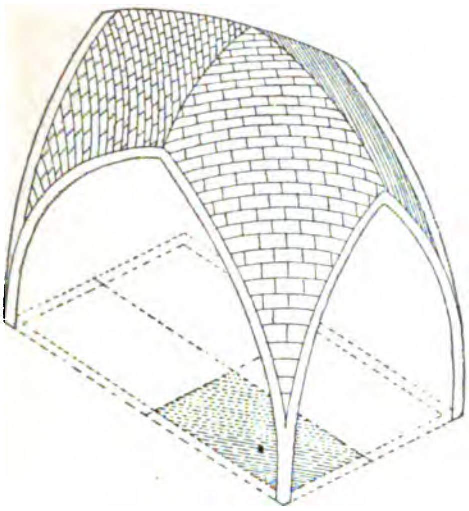


Fig. 104.

8. Dodecapartite. — Fig. 98. The central ring is a not uncommon feature in other varieties, especially quadripartite.

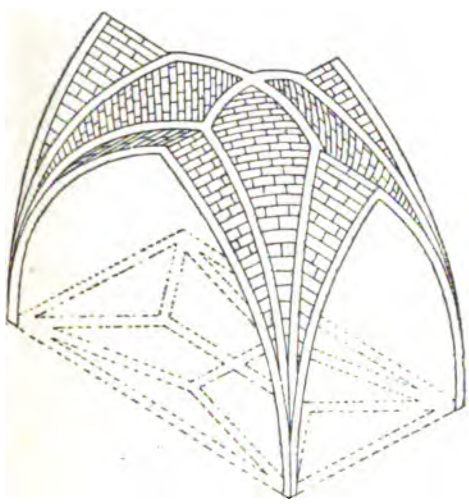


Fig. 105.

9. Groin-ribs interrupted, or diverted and branched
a. Star vaulting. (Fig. 99.) Figs. 100 and 101 are

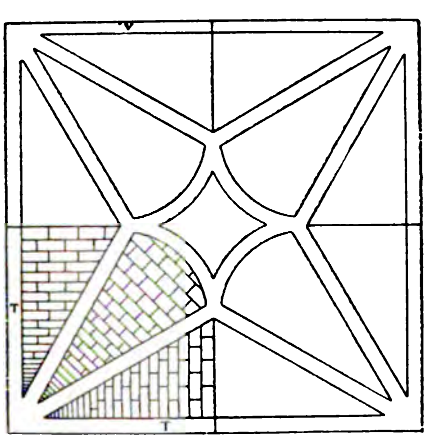


Fig. 106.

other examples from the nave of S. Castor, Coblenz, which, though an early Romanesque building, has Gothic vaulting.

b. Panel vaulting, as it is commonly called. (Fig. 102.)

10. Vaults whose ribs, excepting the ridge, are all arcs of the same circle, differing only in length. They are necessarily domical. They appear to be the immedi-

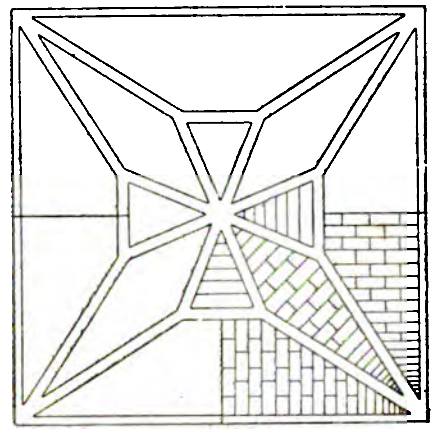


Fig. 107.

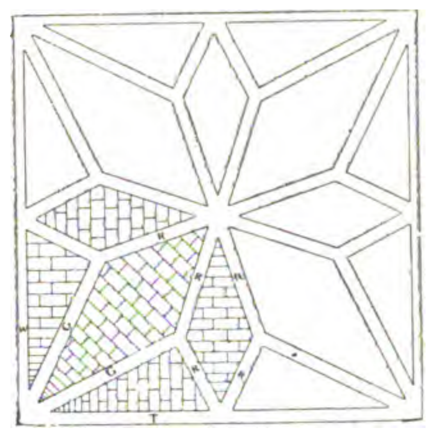


Fig. 108.

ate predecessors of fan-tracery vaulting. Fig. 103 is a quarter plan.

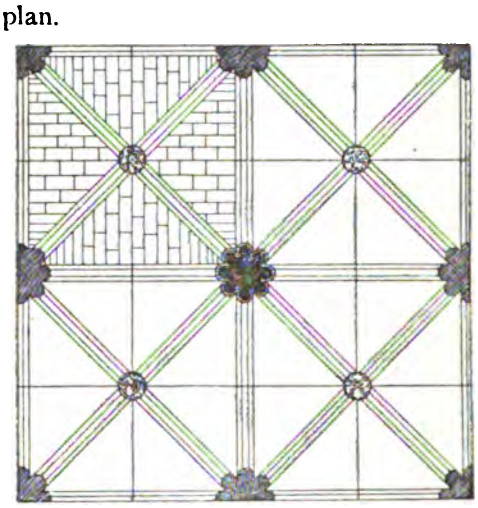


Fig. 109.

11. Groin-ribs (or rather diagonal) lacking. Fig.

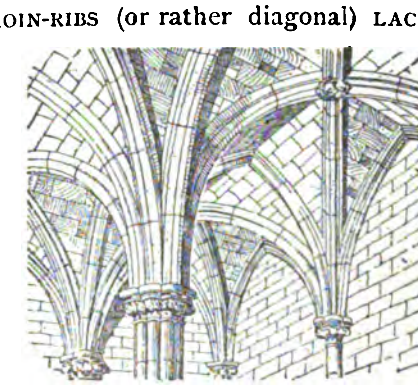


Fig. 110.

104 has transverse and wall-ribs only, but these are really groin-ribs. The panels are usually spheroidal.

Fig. 105 is from Antwerp, and Erfurt; Fig. 106, from Senlis; Fig. 107, from Worms; Fig. 108, from St. Nicholas, Toulouse.

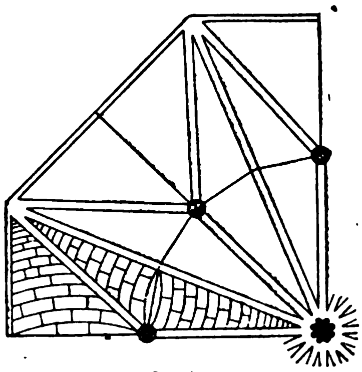


Fig. 111.

12. Vaulting of a square room with a central shaft. Fig. 109 is a plan, and 110 an interior view. It is composed of four quadrilateral vaults. Examples may be

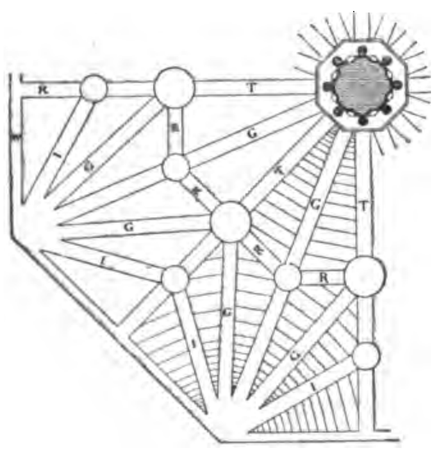


Fig. 112.

found at Crossraguel Abbey, Scotland; at Laon Cathedral, in the choir chapels, etc.

13. Vaulting of octagonal rooms with a central shaft. Fig. 111 is a quarter plan, from the chapter-house of Salisbury Cathedral. Fig. 112 is from Elgin Cathedral.

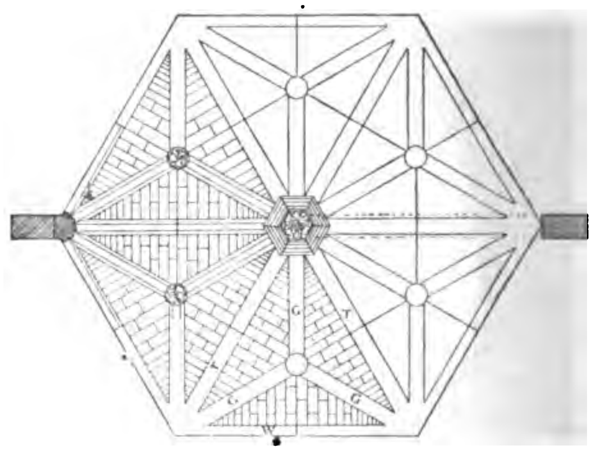


Fig. 113.

Decagonal rooms are vaulted in a similar manner, as in the chapter-house at Lincoln.

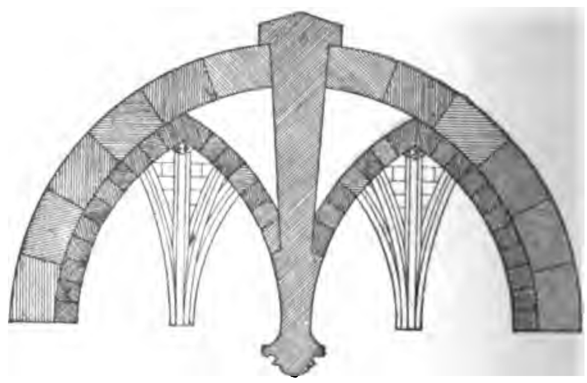


Fig. 114.

14. Pendent Rib Vaults. Fig. 113 is a plan, and 114 a section, from the Lady Chapel at Caudebec.